Development of a ka-band circular waveguide TM_{01}-rectangular waveguide TE_{10} mode converter

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Abstract: The output/input circuit is a core component in all high-power millimeter-wave (MMW) radiation sources, and its performance specifications and reliability directly impact upon the performance of the radiation device. Central to achieving high output power is the development of efficient mode converters. Here we report on the development of , a compact ka-band circular waveguide TM_{01}-rectangular waveguide TE_{10} mode converter. The present mode converter adopts an all-metal waveguide structure and facilitates notable improvement in the system power capacity and is capable of realizing high-power propagation. The mode converter realizes effective mode conversion between high-order and fundamental modes, as well as allowing longitudinal and transverse transmission. Our simulation and empirical findings have shown mode purity as high as 96% in the frequency range of 32.7 -34.6 GHzwith a return loss $S_{11} < -19.3$ dB. The bandwidth of the converter is 2.4 GHz with transmission coefficient $S_{21} \geq -1$ dB. We anticipate these results will provide a strong foundation for the development of ever more sophisticated and high power, compact vacuum electron devices and advanced radiation sources.

Key words: high power radiation; mode converter; ka-band; circular waveguide TM_{01}; rectangular waveguide TE_{10}

1. Introduction

High-power microwave and millimeter-wave (WWM) vacuum electronic device radiation sources (VEDRs) have a considerably wide of applications.; from radar systems and high data rate communications, and non-destructive industrial detection methods, to remote high-resolution imaging in materials research, deep space research and communications devices. To date, almost all high-power MMW VEDRs operate using circular waveguides and high-order TM_{01} modes in order to achieve the required high power capacity [1-3]. In order to achieve improved radiation directionality, multi-channel coupling, and enhanced space transmission, mode converters are commonly employed to convert high-order modes to the rectangular waveguide fundamental mode-TE_{10} which has a peak gain at the aperture in their radiation patterns and, hence, high propagation stability [4-6]. Several high-power radiation systems pump-in or pump-out radio frequency (RF) energy in the rectangular waveguide TE_{10} mode to achieve this[7-9], and the mode excitation of some antennas requires the rectangular waveguide TE_{10} mode. The rectangular waveguide TE_{10} mode itself has a relatively wide range of applications, including …., …, and ….. [ref,ref,ref]. There is a clear practical need, that has yet to be met, for the development of an electromagnetic wave conversion circuit that converts circular waveguide high-order mode-TM_{01} to rectangular waveguide fundamental mode-TE_{10}. Nevertheless, many challenges presently hinder the development of mode converters in high-power radiation devices. Amongst these, perhaps the most pressing is ensuring that the transmission of the RF energy to the load or external circuitry in the desired mode is achieved with a high conversion efficiency and mode purity. The mode converter must offer wide bandwidth and high mode purity in order to withstand frequency instabilities. Given the use of such system in mass-critical application, compactness, dependability and easy integration of the mode conversion system are also critical design considerations.

Incumbent conventional mode converters to date employ serpentine, sectoral or dual bent circular waveguide structures which are difficult to fabricate and install [10-11]. New mode converter structure loaded with dielectric, metallic photonic crystals, and coaxial waveguide structures have also been recently reported [12-14]. Due to a variety of functional limitations of these structures, including …… and …….., many such mode converters are incapable of sustaining high-power microwave or MMW emission compared with more traditional all-metal mode converters that are better suited for use in potentially high-power radiation sources including Virtual Cathode Oscillators (Vircator) [15], Plasma Assisted Slow Wave Oscillators (Pasotron) [16-18], Cerenkov [19], Gyrotron [20], and Travelling Wave Amplifier [21].

In this paper, we have report on the development of a ka-band mode converter for conversion between the TM_{01} and TE_{10} modes. The proposed mode converter is based on an all-metal waveguide structure that improves the power capacity of device markedly over other material platforms. The specific sidewall coupled input/output structure has been employed to realize a transverse input/output high transmission efficiency of …%. Our experimental and simulation results demonstrate that the developed mode converter has many significant advantages such as short circuit, simple circuit structure, , facile manufacturability, low cost, convenient installation, low-attenuation, high mode purity, wide operating bandwidth and considerable conversion efficiency, highlighting the converters wider usefulness in high-power VERs-based radiation sources.

2. Experimental Results and Discussion

2.1 Experimental

The sidewall coupled output mode converter comprises of a top circular waveguide (port 1), a bottom circular waveguide, a short plane with a beam tunnel, a middle coupled circular waveguide, and three rectangular waveguides placed at 120° at the intersection of the coupled section. Two of these waveguides are rectangular short planes and one is the output rectangular waveguide (port 2). A cross-sectional schematic and photograph of the manufactured mode converter are shown in Fig. 1.

The mode converter is processed in three parts: a tapered circular waveguide, an input circular waveguide, and a coupled circular waveguide connected to short-circuit plane. A tapered circular waveguide is attached to the input circular waveguide of the mode converter to match the output port of an existing high-frequency structure in our present laboratory setup. Figure 1b shows the TM_{01} mode and TE_{10} mode field distributions at port 1 and port 2 within the converter. The transmission characteristics of the mode converter are measured using a Vector Network Analyzer (VNA, Make, Model), as shown in Fig. 2a. Since the measurement ports of the VNA are international standardized WR-28 ports, two mode converters are symmetrically connected through a high-frequency system in the experimental measurement, as shown in Fig. 2b. Figure 2c shows typical *S*-parameters measurement, in dB. Our experimental and simulation S_{11} data are plotted in Fig. 3. The simulation and analytical results for the power transmitted through the mode converter and power reflected at the input port are seen to be in excellent agreement with our experimentally measured results. Since a dual mode converter test is adopted, the *S*-parameter values of a single mode converter is necessarily half of the measured experimental data. Our experimental and simulation results demonstrate that our circular waveguide TM_{01} to rectangular waveguide TE_{10} mode converter has outstanding performance from 32.3- 34.7 GHz, showing a transmission coefficient S_{21} of >-1 dB. Moreover, we find two frequencies with peak conversion efficiency(32.9 GHz and 33.8 GHz),as shown in Fig. 3. At the 32.9 GHz peak, S_{21} = -0.18 dB, and S_{11} =- -19.3 dB. The measured conversion efficiency between circular waveguide TM_{01} mode and rectangular waveguide TE_{10} mode is up to 96%. At the 33.8 GHz peak, S_{21} = -0.15 dB, S_{11} = -14.2 dB, and the conversion efficiency between the two modes is up to 97%. Figure 3b shows that the curve of S_{21} has several valleys and peaks resulting from resonant frequencies within the high-frequency cavity. In the following simulations, we demonstrate that S_{21} of a single mode converter has a smooth frequency profile with a bandwidth of -1 dB. The S_{11} of a single mode converter is also tested, as shown in Fig. 3c. These findings demonstrate that S_{11} < -5 dB in range of 32.5-35.0 GHz, and as low as -19 dB at 33.9 GHz.

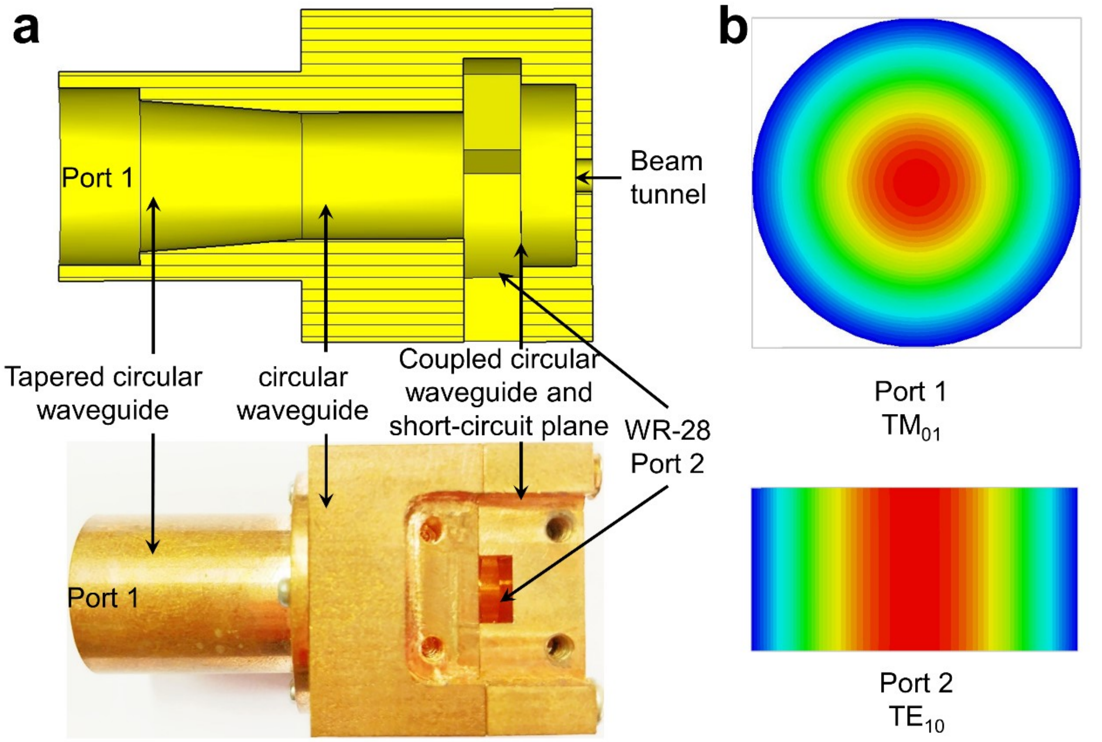

Fig. 1 **a** Cross-section schematic and photograph of the circular waveguide TM_{01}-rectangular waveguide TE_{10} mode converter. **b** Field distributions of TM_{01} mode and TE_{10} mode on port 1 and port 2.

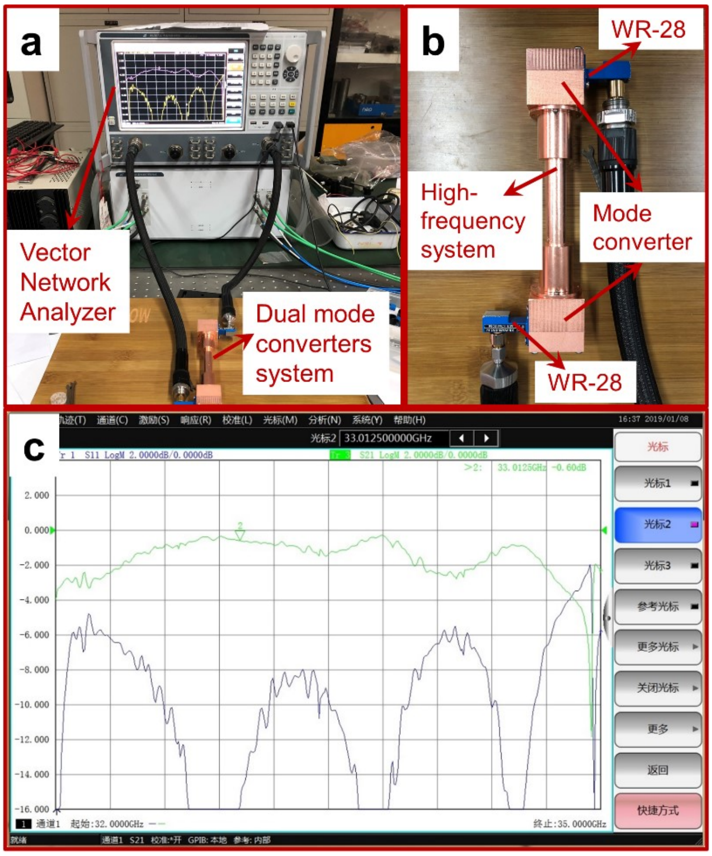

Fig. 2 a. Photograph of the experimental setup. **b** Dual mode converter measurement setup,symmetrically connected through a high-frequency system. **c** Typical S_{11} and S_{21} experimental results.

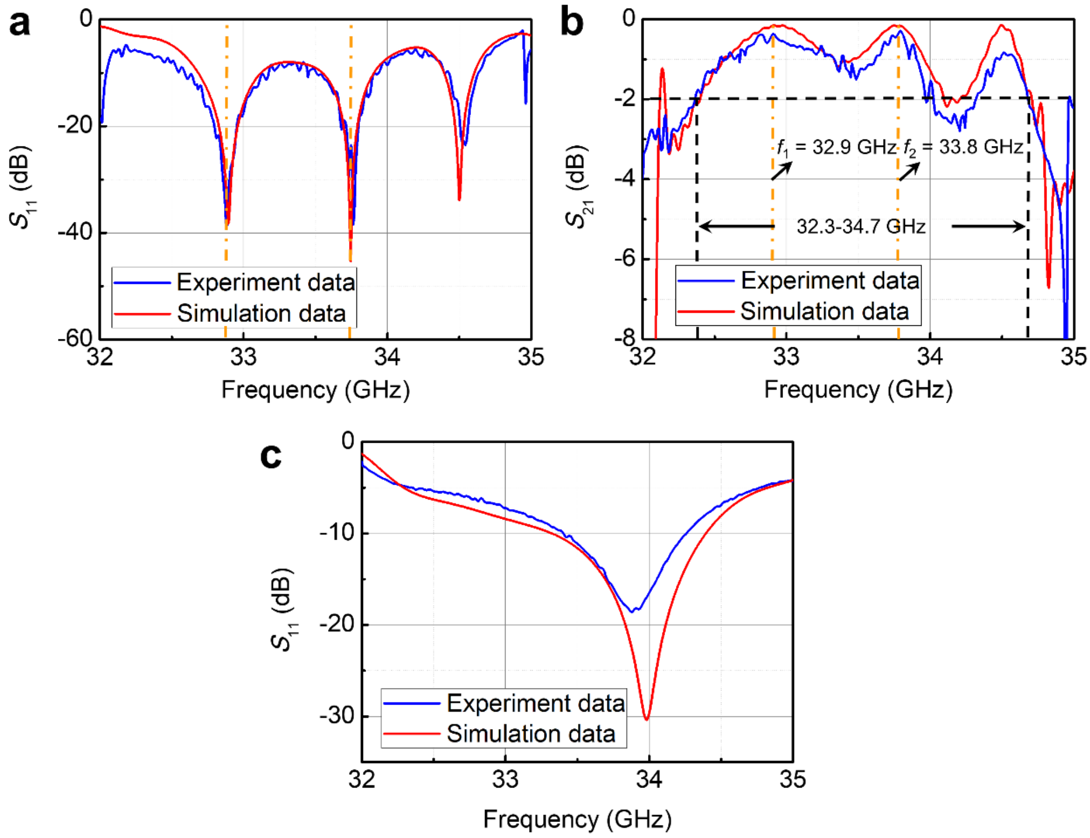

Fig. 3 Comparison of experimental and simulation results of **a** S_{11} and **b** S_{21} of the dual mode converters, and **c** of S_{11} of single mode converter.

2.2 Design and simulation analysis

The 3D rendering of the proposed mode converters vacuum enclosure is shown in Fig. 4a. The mode converter has two ports; a circular waveguide (port 1) and a rectangular waveguide (port 2). In order to obtain high mode conversion efficiency, the design geometries of the mode converter are determined after a series of optimized parametric simulations. From this study we find the following optimized geometries; the radius of the input circular waveguide R_1 is 3.92 mm, the radius of coupled circular waveguide R_2 is 7.27 mm, the radius of circular waveguide short plane R_3 is 5.65 mm, and the radius of beam tunnel R_4 is 1 mm. The output rectangular waveguide and short road rectangular waveguide are standard WR-28 waveguides(7.11 mm × 3.56 mm), the distance between the short surface of the rectangular waveguide and the z axis H_1 is 9.23 mm, and the length of circular waveguide short plane is H_2 is 3.4 mm.

The transmission characteristics of the mode converter are simulated using a commercial time-domain simulation package (CST Microwave Studio). Figure 4b depicts the electric field distribution in the mode converter when the TM_{01} mode is fed into port 1 and the TE_{10} mode is output from port 2. Our simulations demonstrate that the propagation direction of the electromagnetic wave has been transformed, with a peak magnitude field (…V/mm) at the aperture at port 2. The simulated conversion efficiency of the mode converter is plotted in Fig. 4c. Here we use the S_{11} and S_{12} scattering coefficients to describe the transmission characteristics for the different operating frequencies. S_{11}, S_{12} and conversion efficiency have been simulated across the frequency range of 32 - 36 GHz. At the center frequency of 32.73 GHz the transmission coefficient S_{21} ~0, and the reflection coefficient S_{11} = -17 dB. The bandwidth of S_{21} is > -1 dB from 32.4 GHz to 35.0 GHz. Figure 4d shows the variation of mode purity as a function of frequency. The mode purity of the TM_{01} mode is as seen to be as high as 99.5% in the frequency range of 32.7-34.6 GHz. When the frequency exceeds 35.0 GHz, the TE_{11} mode rapidly increases and dominates. The mode converter has a notable mode purity in our operating frequency range.

Simulation optimizations have been conducted to explore the influence of the structural parameters on the transmission characteristics, as shown in Fig. 5. Several dominant parameters have been considered, specifically the radius of the coupled circular waveguide R_2, the radius of the circular waveguide short plane R_3, the distance between the short road surface of the rectangular waveguide, the z axis H_1, and the length of the circular waveguide short plane H_2. The simulation results illustrate that the bandwidth increases as R_3, R_2, H_1, and H_2 decrease. However, reducing R_3 and H_2 results in S_{21} fluctuating dramatically, whilst reducing R_3 reduces the transmission efficiency. Though causing slight fluctuations in S_{21}, reducing R_2 and H_1 can be selected to smooth the transmission coefficient though this reduces the transmission efficiency at center frequency. Our studies suggest an optimal R_3 of 5.65 mm, R_2 of 7.27 mm, H_1 of 9.23 mm, and H_2 of 3.4 mm which are used herein to ensure that the transmission coefficient S_{21} remains suitably smooth (…% variation)whilst retaining a high transmission efficiency (…%) nd broad bandwidth (… GHz).

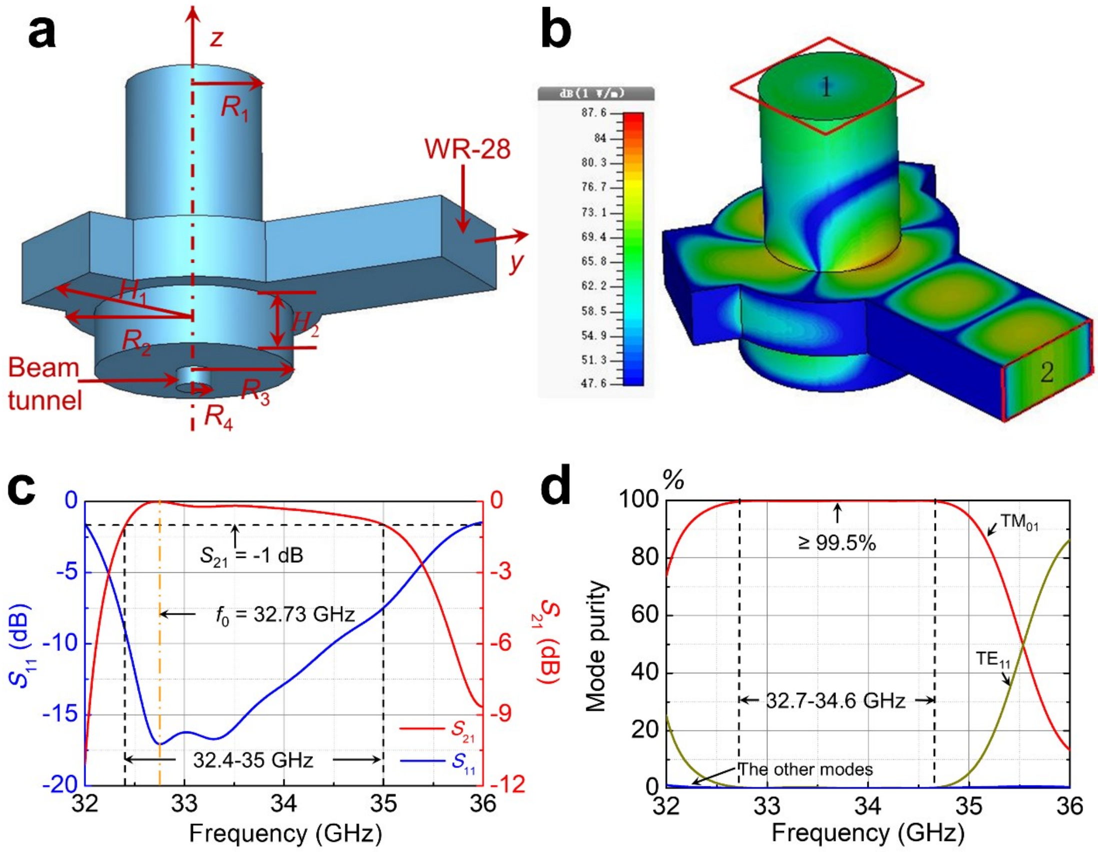

Fig. 4 Mode converter simulation results： **a** 3D rendering of the vacuum enclosure of the mode converter. **b** Electric field distributions in the mode converter when the TM_{01} is fed in port 1 and TE_{10} is output from port 2. **c** *S*-parameters of the mode converter. **d** Variation of mode purity as a function of frequency.

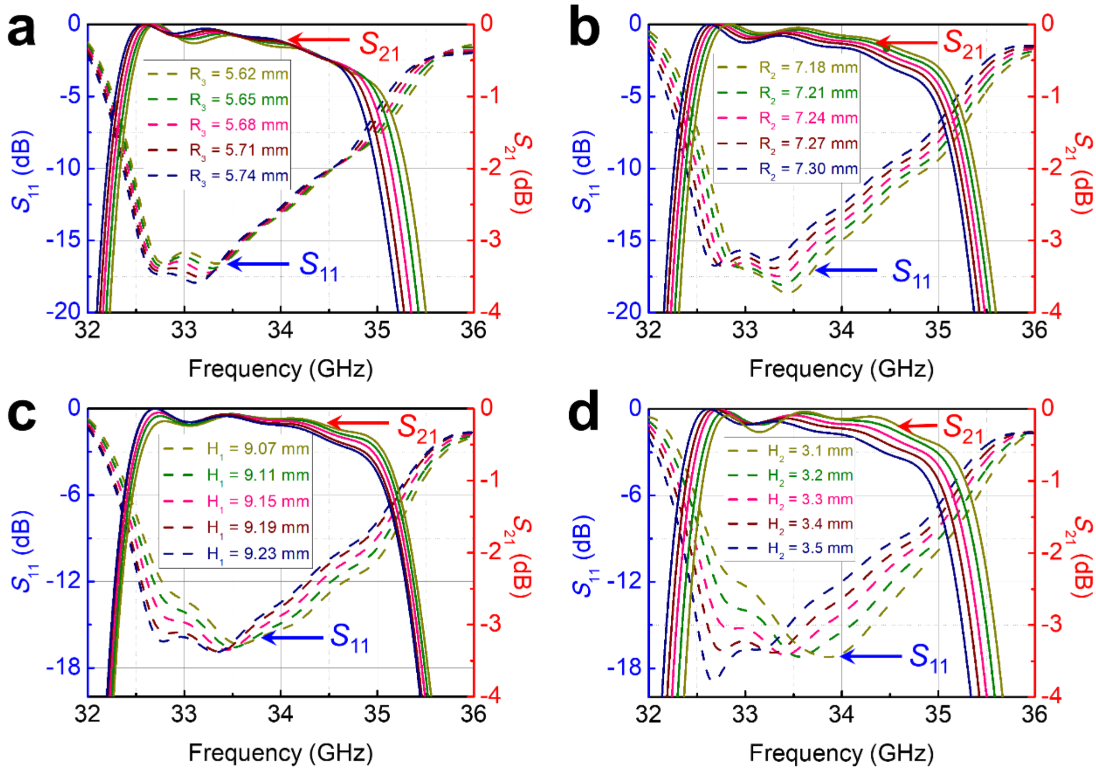

Fig. 5 Parametrically optimized S-parameters of the mode converter as a function of enclosure geometry; the radius of circular waveguide short plane R_3, **b** the radius of coupled circular waveguide R_2, **c** the distance between the short road surface of rectangular waveguide and the z axis H_1, and **d** the length of circular waveguide short plane is H_2.

3. Conclusions

In this paper a ka-band mode converter has been designed and successfully manufactured that is capable of realizing the conversion between circular waveguide TM_{01} and rectangular waveguide TE_{10} modes. Experimental and simulation results collectively show that the frequency bandwidth is 2.4 GHz with a transmission coefficient $S_{21} > -1$ dB, across a frequency range of 32.3 -34.7 GHz. The proposed mode converter has excellent performance at a center frequency of 32.9 GHz with a high conversion efficiency- transmission coefficient S_{21} which reaches up to -0.18 dB, with a return loss S_{11} as low as –19.3 dB, and a modal conversion efficiency of up to 96%. The mode purity of TM_{01} mode has been sown to be > 99.5% in the operating frequency range. The development of mode converters with such high conversion efficiency and high mode purity open up an exciting landscape for future development of a new generation of travelling tubes (TWTs), klystrons, extended interaction klystrons (EIKs), and backward wave oscillators (BWOs) that have the potential to produce output powers in excess of hundreds of Watts

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